

The user wants me to translate a scientific paper title from Chinese to English. The title is: “Root biomechanical properties and influencing factors of two dominant herbs in the landslide area of the upper reaches of the Yellow River, China 后印本”
Let me break this down: - 根系生物力学特性 => Root biomecha...

Authors: The user has provided a name “XING Guangyan” which appears to be a Chinese name. Based on the context of the task (translating academic papers from Chinese to English), this is likely an author name that needs to be translated.

In academic translation, Chinese names are typically transliterated following specific conventions: 1. The surname comes first, followed by the given name 2. The surname is capitalized 3. The given name is typically written with each character capitalized and combined (no hyphen) or separated by a space

For “XING Guangyan” : - Surname: XING (邢 or 行 in Chinese) - Given name: Guangyan (光岩 or 广研 etc.)

Standard academic practice would be to write this as “XING Guangyan” or “Xing Guangyan” . In many English publications, Chinese authors keep the all-caps surname format, so “XING Guangyan” is appropriate.

Since this is just a name and not a full paragraph with tags, I should provide the translation directly. The name should be transliterated, not translated semantically.

The most standard format would be: XING Guangyan

If the user wants the surname first (as is common in academic contexts): XING Guangyan

If they want Western order (given name first): Guangyan XING

But given the context of the previous instructions about preserving academic formatting and the fact that Chinese names in academic papers typically keep the original order, I should keep it as “XING Guangyan” .

However, the user hasn't provided any tags or actual content to translate. They've just given a name. The instructions say "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."

So I should just output: XING Guangyan

Wait, let me reconsider. The name "XING Guangyan" is already in Pinyin (the Romanization system for Chinese). It's not in Chinese characters. So it's already transliterated. The task is to translate from Simplified Chinese to English, but this is already in a form used in English academic contexts.

Perhaps the user wants me to format it according to academic conventions? Or maybe they want me to translate it as if it were in Chinese characters? But they provided it in Pinyin.

Given the strict instructions, I should treat this as a simple case where the input is already in the appropriate format for English academic text. The name "XING Guangyan, The user has provided a very short input: HU Xiasong". This appears to be a name, likely Chinese. Let me analyze what this could be:

1. It could be a person's name that needs to be translated or transliterated
2. It could be part of a larger document that I'm supposed to translate
3. The user might be testing the system

Looking at the context, the user previously gave me instructions about translating scientific papers with specific requirements about preserving LaTeX, citations, and tags. However, the current input is just "HU Xiasong" with no tags, no LaTeX, no citations.

The name "HU Xiasong" is a Chinese name. In academic contexts, Chinese names are typically: - Either kept in their original pinyin form - Or transliterated following specific conventions

"HU" is the surname (family name) and "Xiasong" is the given name. In English academic writing, Chinese names are usually written with the surname first and given name second, either as "HU Xiasong" or "Hu Xiasong" (with only the first letter capitalized). The all-caps "HU" is often used in some citation styles to clearly identify the surname.

Since there are no tags, no LaTeX, and no other content, I should simply return the name as is, or perhaps with minor capitalization adjustments if needed. However, the instructions say "Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent)."

Given that this is just a name, and names are typically not "translated" but rather transliterated or kept as is, the most appropriate action would be to return the name in a standard academic format. The input is "HU Xiasong" which is already in pinyin and appears to be in a format where the surname is in all caps, which is common in some academic databases.

I should check if there's any standard convention: - In many Chinese academic

contexts, names are written as “HU Xiasong” (surname in caps) - In Western contexts, it’s often “Hu Xiasong” or “Xiasong Hu” (surname last)

Since the user hasn’t provided context about where this name appears, and the instructions are about translating scientific papers (which often maintain the original name format), I should probably keep it as is: “HU Xiasong”

But wait - the user might be, LIU Changyi, The user wants me to translate a Chinese name “ZHAO Jimei” into English. This appears to be a person’s name.

Looking at the name: - 赵 (Zhào) is a common Chinese surname, which is typically written as “Zhao” in English - 济美 (Jíměi) is the given name

The user has already provided it in English format: “ZHAO Jimei” with the surname in all caps and the given name capitalized. This is a standard academic formatting for Chinese names in English publications.

However, I need to check the context. The user just provided “ZHAO Jimei” without any surrounding text or tags. The instructions say: - “Translate from Simplified Chinese to English with the highest accuracy and academic tone.” - “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).” - “Preserve ALL …paragraph wrapper tags EXACTLY”

Since there’s no tag in the input, I should just return the name as is. The name is already in English format, so no translation is needed. I should just return it exactly as provided.

But wait - is “ZHAO Jimei” the input, or is it just a test? The instructions are very specific about preserving tags. Since there are no tags here, I should just return the text as is.

Let me re-read the instructions carefully: - “Translate from Simplified Chinese to English” - The input is “ZHAO Jimei”

This is already in English (or rather, it’s a Chinese name romanized into English). So there’s nothing to translate. I should return it exactly as provided.

The format “ZHAO Jimei” is correct for academic contexts - surname in all caps, given name with initial capital. This follows the convention used in many academic papers.

So my output should simply be: ZHAO Jimei

No tags are needed since none were in the input. The instructions say to preserve them if they exist, but they don’t exist here.

Actually, let me reconsider. The user might be testing if I understand that names should be kept as is. The name “ZHAO Jimei” is already in the correct English academic format. I should not modify it.

The simplest and most, LU Haijing, The user has provided a very short input: “LI Huatan”. This appears to be a Chinese name. Let me analyze this carefully.

The instruction says: - Translate from Simplified Chinese to English with the highest accuracy and academic tone - Preserve ALL LaTeX commands and placeholders exactly - Preserve ALL citation commands - **PRESERVE ALL ...paragraph wrapper tags EXACTLY** - Maintain academic tone and formal scientific writing style - Use precise technical terminology - obey the glossary strictly - Preserve section structure and paragraph organization - Translate all content completely - do not omit any information

The input is just “LI Huatan” with no paragraph tags, no LaTeX, no citations. It’s just a name.

According to the glossary: - 机器学习 => machine learning - 深度学习 => deep learning

But “LI Huatan” is a name, not a technical term from the glossary.

In academic contexts, Chinese names are typically transliterated following specific conventions: 1. The surname comes first (LI) and the given name comes second (Huatan) 2. In English publications, it’s common to either: - Keep the original order: LI Huatan - Or reverse to Western order: Huatan Li

However, the most standard and respectful approach in academic translation is to preserve the original Chinese name as it is, since names are proper nouns that shouldn’t be translated but rather transliterated. “LI Huatan” is already in Pinyin (the romanization system for Chinese), so it should remain unchanged.

The instruction says “Translate from Simplified Chinese to English” - but a name isn’t really “translated” - it’s a proper noun that should be preserved. The most accurate approach is to keep it exactly as written: “LI Huatan” .

Since there are no tags in the input, I should not add any. The output should be just the name itself.

Let me double-check the requirements: - Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent) - Keep one output paragraph per input paragraph; do not merge or split paragraphs - **Maintain exact count and IDs of ...tags** - if input has N paragraph tags, output must have exactly N paragraph tags with matching IDs

The input has 0 paragraph tags, so the output should have 0 paragraph tags. It should, The user has provided a single name: “LI Guorong” . This appears to be a Chinese name that needs to be translated or romanized.

The name “LI Guorong” is already in Pinyin romanization format. In Chinese names: - The surname comes first: “LI” (李) - The given name comes second: “Guorong” (国荣 or 国蓉, etc.)

Since the name is already in standard Pinyin format, which is the standard for academic and scientific contexts, no translation is needed. The name should remain as “LI Guorong” .

However, I need to consider the context. The user might be asking for: 1. The English representation (which is already correct as “LI Guorong”) 2. The actual translation of the characters (which would be problematic without knowing the exact characters) 3. How to format it in an academic paper

Given the critical requirements about preserving structure and the fact that this is a name (likely an author name), I should: - Keep it exactly as is - Not add any explanation - Not add any tags since there are none in the input

The input is simply “LI Guorong” with no tags, no LaTeX, no citations. According to the rules, I should return ONLY the translated text. Since it’s already in the correct format, I should return it unchanged.

Wait, let me re-read the instructions carefully. The user provided “LI Guorong” - this is just a name. The system prompt says I’m a professional scientific translator and gives me rules about preserving LaTeX, citations, and tags. But the input doesn’t contain any of those.

The most important rule here is: “Return ONLY the translated text for the given input (no explanations, no quotes, no headings you invent).”

Since “LI Guorong” is already in proper Pinyin format, which is the standard for English academic papers, the “translation” is simply to keep it as is. I should not add any tags or explanations.

Let me double-check: Is there any ambiguity? - LI could be “Li” or “LEE” but “LI” is standard Pinyin - Guorong is the given name

In academic contexts, Chinese names are typically written in Pinyin, either as “LI Guorong” or “Guorong Li” depending on the journal style. Since the input is “LI Guorong”, I, ZHU Haili, The user has provided a name “LIU Yabin” and wants me to translate it. However, this is not a paragraph with tags, LaTeX commands, or any of the structural elements described in the instructions. The instructions are very specific about preserving ...tags, LaTeX commands, and citation commands.

Since the input is just a name “LIU Yabin”, and the instructions require me to: 1. Preserve ALL ...paragraph wrapper tags EXACTLY 2. Preserve ALL LaTeX commands and placeholders exactly 3. Preserve ALL citation commands exactly 4. Return ONLY the translated text for the given input (no explanations, no quotes, no headings) 5. Keep one output paragraph per input paragraph

But there are no tags, no LaTeX, no citations. The input is just a standalone name. The instructions say “Translate from Simplified Chinese to English with the highest accuracy and academic tone.”

For Chinese names, the standard academic translation is to: - Keep the surname in uppercase: LIU - Capitalize the given name: Yabin - Or use the format: Liu Yabin

In academic contexts, Chinese names are typically written as “Liu Yabin” (surname first, capitalized) or sometimes “Yabin Liu” (Western order). The most common and standard format in academic papers is to keep the original order: Liu Yabin.

However, the instructions are extremely specific about preserving structural elements. Since there are no structural elements to preserve, I should just provide the translation of the name itself.

The name “LIU Yabin” is already in a format that could be considered partially translated - the surname is in uppercase. In proper academic English translation, it would typically be rendered as “Liu Yabin” or “Yabin Liu”. Given that this appears to be a standalone name (likely an author name), and considering academic conventions, “Liu Yabin” would be the most appropriate translation.

But wait - the instructions say “Return ONLY the translated text for the given input”. The input is “LIU Yabin”. If I just output “Liu Yabin”, that would be the translation. However, the instructions also emphasize preserving tags. Since there are none, I don’t need to add them.

Let me reconsider. The user might be testing if, The user has provided a very short input: “HU Xiasong”. This appears to be a name, likely Chinese. The task is to translate from Simplified Chinese to English with the highest accuracy and academic tone, following the critical requirements and output rules provided.

Let me analyze this: 1. “HU Xiasong” is a Chinese name 2. In academic contexts, Chinese names are typically transliterated following specific conventions 3. The surname is “HU” (胡) and the given name is “Xiasong” (夏松) 4. In English academic papers, Chinese names are usually written in one of these formats: - HU Xiasong (all caps for surname) - Hu Xiasong (only first letter capitalized) - Xiasong Hu (Western order, given name first)

The most common and standard format in academic literature is to keep the original order (surname first) with the surname in all caps: HU Xiasong. This is particularly true for translation tasks where we’re preserving the original name format.

Since this is just a name, there are no: - LaTeX commands to preserve - placeholders - citation commands - ...tags - mathematical expressions - technical terminology from the glossary

The glossary provided includes: 机器学习 => machine learning 深度学习 => deep learning

But these are not relevant to this input.

The output should be just the translated name. Since names are transliterated, not translated, “HU Xiasong” is already in the correct format for an academic English context. I should preserve it exactly as is.

However, I need to check if there are any tags. The user input is just “HU

Xiasong” without any tags. The instructions say “Return ONLY the translated text for the given input” and “Keep one output paragraph per input paragraph; do not merge or split paragraphs.”

Since there’ s no paragraph tag in the input, I should not add one. I should just return the name as is.

Wait, let me re-read the instructions carefully. The user provided “HU Xiasong” as the input. The system prompt says I should translate from Simplified Chinese to English. The name “HU Xiasong” is already in Pinyin (Romanized Chinese).

In academic contexts, when a Chinese name is already in Pinyin, it’ s typically left as is. The format “HU Xiasong

Date: 2025-12-15T18:43:36+00:00

Abstract

The user wants me to translate a scientific abstract from Simplified Chinese to English. Let me analyze the requirements:

1. Critical Requirements:

- Preserve ALL LaTeX commands and placeholders exactly
- Preserve ALL citation commands ([?], ??, (??), etc.) exactly
- **PRESERVE ALL ...paragraph wrapper tags EXACTLY**
- Maintain academic tone and formal scientific writing style
- Use precise technical terminology - obey the glossary strictly
- Preserve section structure and paragraph organization
- Translate all content completely - do not omit any information

2. Output Rules:

- Return ONLY the translated text (no explanations, no quotes, no headings)
- Keep one output paragraph per input paragraph
- **Maintain exact count and IDs of ...tags**
- Do NOT add Markdown formatting unless present in source
- Preserve original line breaks within the paragraph when meaningful

3. Formatting Guidelines:

- Keep mathematical expressions in original LaTeX format
- Preserve equation numbers and references
- Maintain proper academic paragraph structure
- Use formal scientific language

4. Glossary:

- 机器学习 => machine learning
- 深度学习 => deep learning

Looking at the input text, I notice: - It’ s a single paragraph (no explicit tags in the input) - It contains scientific content about soil erosion, vegetation roots, and mechanical properties - There are some statistical notations like $P < 0.010$, $P < 0.001$, etc. - There are numerical values and units (MPa, mm/min, etc.) -

No LaTeX commands or math placeholders are present in this particular text -
No citation commands

Since there are no tags in the input, I should NOT add them. The instruction says “PRESERVE ALL `…`paragraph wrapper tags EXACTLY” - if none exist, I don’ t add them. I should just translate the text as a single paragraph.

Let me translate the content carefully, maintaining academic tone:

Original Chinese text: “Soil erosion and shallow landslides in the upper reaches of the Yellow River, China, are increasing due to extreme climate events and human disturbances. The biomechanical properties of vegetation roots play an important role in soil stabilization and fixation, as they resist soil erosion and shallow landslides in this area. However, the biomechanical properties of the roots of dominant herbs and their influencing factors in this area remain poorly understood. Therefore, we selected two dominant herbs in this area, *Stipa aliena* Keng and *Poa crymophila* Keng, and carried out a series of uniaxial tensile tests on the roots of the two herbs under different treatments. Meanwhile, the effects of root diameter, plant species, gauge length, root water content, and loading rate on the biomechanical properties of the two herbs’ roots were analyzed. The results showed that root diameter was the most significant factor affecting the root biomechanical properties ($P<0.010$), and root tensile force displayed a positive power law relationship with root diameter, whereas root tensile strength and Young’ s modulus followed negative power law correlations with root diameter, and fracture strain increased linearly with root diameter. Root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those of *P. crymophila* ($P<0.001$), which was mainly due to the higher lignin content and lignin:cellulose ratio of *S. aliena* roots. During uniaxial tensile process, hydrated roots exhibited elastic-plastic-brittle behavior, whereas dried roots exhibited elastic-brittle behavior. Root fracture strain of the two herbs was significantly lower under 100 mm gauge length than under 50 mm gauge length ($P<0.001$), and the Young’ s modulus was significantly greater ($P<0.050$). Tensile strength and fracture strain of hydrated roots of the two herbs were significantly greater than those of dried roots ($P<0.050$), whereas the Young’ s modulus was significantly lower ($P<0.001$). Root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater under 20 mm/min loading rate than under 200 mm/min loading rate ($P<0.050$), whereas loading rate had no significant effect on the root biomechanical properties of *P. crymophila* ($P>0.050$). Fibrous roots of the two herbs were well developed, with relatively high tensile strengths and Young’ s moduli of 78.498 and 837.901 MPa for *S. aliena*, and 67.541 and 901.184 MPa for *P. crymophila*, respectively. The two herbs can stabilize soil and prevent soil erosion and can be used as pioneer species for ecological restoration in the upper reaches of the Yellow River. These results provide a theoretical basis for soil erosion and shallow landslide control in the giant landslide area of the upper reaches of the Yellow River.”

Wait, I need to check if there are any tags. Looking at the input again, I see it’ s just plain text without any tags. So I should just provide the translation as

plain text without adding any tags.

Let me refine the translation to ensure it's academically appropriate:

- “upper reaches of the Yellow River” - good
- “extreme climate events and human disturbances” - good
- “biomechanical properties of vegetation roots” - good
- “soil stabilization and fixation” - could be “soil stabilization and reinforcement”
- “dominant herbs” - good
- “uniaxial tensile tests” - good
- “gauge length” - good technical term
- “root water content” - good
- “loading rate” - good
- “positive power law relationship” - good
- “negative power law correlations” - good
- “fracture strain” - good
- “lignin content and lignin:cellulose ratio” - good
- “elastic-plastic-brittle behavior” - good
- “elastic-brittle behavior” - good
- “fibrous roots” - good
- “pioneer species” - good
- “ecological restoration” - good
- “giant landslide area” - good

The translation looks solid. I need to make sure I maintain the formal academic tone throughout. Let me review once more for any subtle improvements:

- “are increasing” -> “have been intensifying” might be more academic
- “play an important role” -> “play a crucial role” or “

Full Text

Preamble

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Root Biomechanical Properties and Influencing Factors of Two Dominant Herbs in the Landslide Area of the Upper Reaches of the Yellow River, China

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Abstract

Soil erosion and shallow landslides in the upper reaches of the Yellow River, China, are increasing due to extreme climate events and human disturbances. The biomechanical properties of vegetation roots play an important role in soil stabilization and fixation, as they resist soil erosion and shallow landslides in this area. However, the biomechanical properties of the roots of dominant herbs and their influencing factors in this area remain poorly understood. Therefore, we selected two dominant herbs in this area, *Stipa aliena* Keng and *Poa crymophila* Keng, and carried out a series of uniaxial tensile tests on the roots of the two herbs under different treatments. Meanwhile, the effects of root diameter, plant species, gauge length, root water content, and loading rate on the biomechanical properties of the two herbs' roots were analyzed. The results showed that root diameter was the most significant factor affecting the root biomechanical properties ($P < 0.010$), and root tensile force displayed a positive power law relationship with root diameter, whereas root tensile strength and Young's modulus followed negative power law correlations with root diameter, and fracture strain increased linearly with root diameter. Root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those of *P. crymophila* ($P < 0.001$), which was mainly due to the higher lignin content and lignin:cellulose ratio of *S. aliena* roots. During the uniaxial tensile process, hydrated roots exhibited elastic-plastic-brittle behavior, whereas dried roots exhibited elastic-brittle behavior. Root fracture strain of the two herbs was significantly lower under 100 mm gauge length than under 50 mm gauge length ($P < 0.001$), and the Young's modulus was significantly greater ($P < 0.050$). Tensile strength and fracture strain of hydrated roots of the two herbs were significantly greater than those of dried roots ($P < 0.050$), whereas the Young's modulus was significantly lower ($P < 0.001$). Root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater under 20 mm/min loading rate than under 200 mm/min loading rate ($P < 0.050$), whereas loading rate had no significant effect on the root biomechanical properties of *P. crymophila* ($P > 0.050$). Fibrous roots of the two herbs were well developed, with relatively high tensile strengths and Young's moduli of 78.498 and 837.901 MPa for *S. aliena*, and 67.541 and 901.184 MPa for *P. crymophila*, respectively. The two herbs can stabilize soil and prevent soil erosion and can be used as pioneer species for ecological restoration in the upper reaches of the Yellow River. These results provide a theoretical basis for soil erosion and shallow landslide control in the giant landslide area of the upper reaches of the Yellow River.

Keywords: herbaceous plants; root biomechanical properties; root diameter; gauge length; root water content; loading rate

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1 Introduction

Many giant landslides occur in the upper reaches of the Yellow River, which are spatially distributed along the river channel. The giant landslides from Longyangxia area to Liujiaxia area are the most typical in the Yellow River (Lan et al., 2022). In recent years, increased precipitation, frequent extreme weather, and climate events, coupled with overgrazing and human engineering activities, have led to severe soil erosion and shallow landslides, which severely threaten the ecological and geological security of the area. Therefore, how to effectively prevent and mitigate soil erosion and shallow landslides in the giant landslide areas of the upper reaches of the Yellow River has become an urgent issue.

Vegetation is the most commonly used biological measure for soil and water conservation and can not only intercept rainfall and reduce the erosive force of rainfall but also improve soil structure and enhance soil erosion resistance (Shi et al., 2018). Plant roots can improve soil shear strength by anchoring soil layers and changing their hydrological characteristics to control shallow landslides (Eab et al., 2015; Wang et al., 2019; Nguyen et al., 2020; Ongpaporn et al., 2022; Prasetyaningtiyas et al., 2024). Prasetyaningtiyas et al. (2024) studied the effects of the roots of *Chrysopogon zizanioides* (L.) Roberty on the hydraulic behavior of an unsaturated soil slope. Results revealed that the roots significantly affected the initial suction of the slope by increasing the air intake value of soil, and the suction provided by the roots and additional cohesion increased the stability of the slope under rainfall conditions. Root biomechanical properties, including tensile strength, tensile strain, and Young's modulus, are key indicators used to characterize the physical contribution of vegetation to shallow landslides and soil erosion (Mao et al., 2018). Understanding the biomechanical properties of plant roots is essential for improving soil stability, especially in areas prone to landslides and erosion (Burylo et al., 2012; Stokes et al., 2014; Apriyono et al., 2023).

Studies have shown that root diameter, root chemical composition and microstructure, gauge length, root water content, and loading rate significantly affect root biomechanical properties (Genet et al., 2005; Li et al., 2015; Melese et al., 2021; Wu et al., 2021; Yang et al., 2025). Numerous scholars have conducted detailed studies on the relationship between root diameter and tensile strength, concluding that tensile strength of roots follows a power law relationship with root diameter (Gray and Sotir, 1996; De Baets et al., 2008; Ekeoma et al., 2021; Phan et al., 2021; Zhang et al., 2023). Previous studies attributed this result to the variation of root chemical composition with root diameter (Genet et al., 2005; Zhao and Zhang, 2007; Zhang et al., 2014; Zhu et al., 2020; Yang et al., 2025). Some studies reported that root cellulose content decreased with increasing root diameter and that root tensile strength was positively correlated with cellulose content (Genet et al., 2005; Zhao and Zhang, 2007; Yang et al., 2025). However, Zhang et al. (2014) and Zhu et al. (2020) reported that with increasing root diameter, root cellulose content increased and lignin content de-

creased, and root tensile strength was positively correlated with lignin content. In addition, plant roots have complex layered structures, and their mechanical properties are closely related to their microstructure (Jiang et al., 2013). Zhang et al. (2022) studied the relationship between root mechanical properties and microstructure in *Blysmus sinocompressus* Tang & F. T. Wang, *Kobresia capillifolia* (Decne.) C. B. Clarke, and *Potentilla fruticosa* (L.) Rydb., revealing that tensile strength of herbaceous plant roots is related primarily to the proportion of vascular cylinder area, whereas in shrub roots, it is associated mainly with the proportions of periderm and secondary xylem area. Furthermore, Jiang et al. (2013) examined the roots of three broadleaf species (*Betula platyphylla* Sukaczew, *Quercus mongolica* Fisch. ex Ledeb., and *Ulmus pumila* L.) and reported that percentage of wood fiber area in root cross-section had the greatest positive influence on the root tensile force, whereas proportion of phloem area in the root cross-section presented the strongest positive correlation with root tensile strength. However, influences of root water content, gauge length, and loading rate on the root biomechanical properties have received less attention, although they are correlated with slope stability.

Variations in root moisture content significantly influence root tensile properties (Yang et al., 2016a; Boldrin et al., 2018; Zhang et al., 2018; Zhang et al., 2019; Ekeoma et al., 2021; Wu et al., 2021). Moderate water loss may increase root tensile strength, whereas excessive dehydration reduces elongation capacity, leading to diminished tensile strength (Yang et al., 2016b; Zhang et al., 2018; Capilleri et al., 2019). Some studies have shown that tensile force, tensile strength, and Young's modulus increase, but that fracture strain decreases after hydrated roots are dried (Zhang et al., 2019; Ekeoma et al., 2021; Wu et al., 2021). Gauge length significantly affects tensile force, tensile strength, and fracture strain of the roots, and gauge length was negatively correlated with tensile force, tensile strength, and fracture strain of the roots (Zhang et al., 2012; Zhang et al., 2021; Fu et al., 2024). However, when the root biomechanical properties of *Medicago sativa* L. were studied, Mao and Geng (2023) found that root gauge length had no significant effect on root tensile force or tensile strength. Numerous studies have indicated that tensile loading rate had no significant influence on root biomechanical properties (Zhang et al., 2012; Melese et al., 2021; Wu et al., 2021). However, Li et al. (2015) researched the basic mechanical properties and influencing factors of the roots of *Pinus tabulaeformis* Carrière and *Larix gmelinii* var. *principis-rupprechtii* (Mayr) Pilger, and reported that loading rate significantly affected tensile force and tensile strength of the roots and was negatively correlated with tensile force and tensile strength of the roots.

In summary, previous studies have focused primarily on the relationships between root biomechanical properties and root diameter. There are few studies on the effects of root water content, gauge length, and loading rate on root biomechanical properties, and no unified conclusion has been reached yet. This study focused on two dominant herbs, *Stipa aliena* Keng and *Poa crymophila* Keng, in the Xijitan landslide area of the upper reaches of the Yellow River.

Through uniaxial tensile tests combined with nonlinear regression and analysis of variations (ANOVA), the root biomechanical properties and their influencing factors were studied. This study aims to: (1) determine the relationships among root tensile force, tensile strength, fracture strain, Young's modulus, and root diameter of the two herbs; (2) characterize the stress-strain relationships of the two herbs during single-root tensile process; (3) investigate the influences of root chemical composition and microstructure on root biomechanical properties; and (4) evaluate the effects of gauge length, root moisture content, and loading rate on root biomechanical properties. The results of this research might provide a theoretical basis for scientific prevention and control of geological disasters such as soil erosion and shallow landslides in the upper reaches of the Yellow River.

2.1 Study Area and Root Sampling

Roots of the two herbs were collected from Xijitan giant landslide (36°06'N, 101°27'E), located in the transition zone between mountain and valley of the Yellow River in the Guide Basin, Qinghai Province, China. The study area has a plateau continental climate, a long light duration, and strong solar radiation. Spring is dry and windy, summer is short and cool, autumn is wet and rainy, winter is long and dry, and daily temperature difference is large. Annual average temperature is 7.2°C, the maximum temperature is 34.0°C, and the minimum temperature is -23.8°C. Average annual precipitation is 250-559 mm, which mainly concentrates from June to August. Average annual evaporation is 1895 mm.

Dominant plants in the Xijitan giant landslide area are herbaceous plants, among which *S. aliena* and *P. crymophila* are the most widely distributed (Zhao et al., 2024). Both herbs are of scattered root type, with dense roots and strong soil and water conservation effects (Fu et al., 2023). Therefore, the two herbs were selected as the research material in this study, and photos of their appearance and fresh roots are shown in Figure 1 [Figure 1: see original paper]. Through field plot investigations, vegetation coverage of *S. aliena* was 37.00%, vegetation plant height was 4.10 (± 1.10) mm ($n = 30$); vegetation coverage of *P. crymophila* was 50.00 (± 0.70) mm ($n = 30$). Roots of the two herbs were excavated in June 2023. When the two plant roots were collected, plant growth range was expanded by 10 cm outside the edge, and soil and roots in the range were excavated as a whole with a shovel. Roots were placed in an insulated box above ice with original soil and quickly sent to the laboratory to keep the roots fresh. In the laboratory, roots were carefully selected from the soil, and completely straight roots were cut with scissors, after which roots were numbered in plastic bags and then refrigerated at 4.0°C until use. Root diameters ranging from 0.10 to 0.45 mm were selected. Root tests were completed within 7 d after sampling.

Fig. 1 Appearance and fresh roots of two dominant herbs. (a), *Stipa aliena* Keng; (b), *Poa crymophila* Keng.

2.2 Root Tensile Tests

To investigate the effects of plant species, root water content, gauge length, and loading rate on root biomechanical properties, we carried out four treatments on the root samples of two herbs (Table 1). Based on root lengths of the two collected herbs and referring to the research on root tensile properties of *Kochia scoparia* (L.) Schrad. and *Artemisia sacrorum* Ledeb. by Zhang et al. (2021), we designed two different gauge lengths (50 and 100 mm). According to the study of Wu et al. (2021), we set two loading rates (20 and 200 mm/min) and two types of water status of roots (hydrated roots and oven-dried roots). Hydrated root samples were prepared by soaking the roots of tested plants in tap water for at least 24 h, and hydrated root samples were then placed in an oven at 50.0°C for at least 24 h until a constant weight (Fig. 2 [Figure 2: see original paper]).

Uniaxial tensile tests were conducted on the roots of two herbs subjected to different treatments using an HY-0580 electronic universal testing machine (Hengyi Testing Instruments Co., Ltd., Shanghai, China), and tensile force, tensile strength, fracture strain, and Young's modulus were measured. Tensile rate of instrument can be set to 500 mm/min, and accuracy of tension sensor and displacement sensor is $\pm 0.50\%$. During testing, a pair of fixtures were used to secure root segment: one was manually clamped onto testing machine base and the other was connected to tension sensor. To reduce breakage or slippage of root segment at both ends of fixture, we pasted medical tape on both ends of upper and lower fixtures to increase friction between root segment and fixture. When root fracture occurred near the middle of sample, test was considered successful, and each group of tensile samples ensured that the number of effective roots was not less than 60. After root segment was broken, the maximum tensile force and corresponding elongation length were recorded. Root diameter at fracture position was measured three times using a digital caliper (Chen et al., 2018), and the average value was recorded. Tensile strength, fracture strain, and Young's modulus for a single root can be calculated using Equations 1-3 (Zhang et al., 2023), respectively.

where T_r is the tensile strength of a single root (MPa); F is the tensile force of a single root at the breaking point (N); D is the root diameter (mm); ε_r is the fracture strain of a single root (%); ΔL is the deformation of a single root at root failure (mm); L is the clamping length of the root, that is, the root gauge length (mm); and E_r is the Young's modulus of a single root (MPa).

Fig. 2 Photos of the roots of two herbs in both water-absorbing and oven-dried status. (a), hydrated roots of *S. aliena*; (b), hydrated roots of *P. crymophila*; (c), oven-dried roots of *S. aliena*; (d), oven-dried roots of *P. crymophila*.

2.3 Determination of Root Chemical Composition

Owing to small root diameter of the two herbs used in this study, after biomechanical property testing, roots were directly classified by plant species for chem-

ical composition analysis, and analysis indices were cellulose, lignin, and hemicellulose. Neutral detergent-2 N HCl-H₂SO₄ method was used to measure (Chi, 2012). Briefly, about 1 g root sample was weighed, stirred, and heated with 30 mL of neutral detergent reagent (NDR) to dissolve and remove pectin and other substances in the sample. Remaining substance was neutral detergent fiber (NDF), and 20 mL of 2 N HCl was used to hydrolyze hemicellulose. After pH of hydrolysate was adjusted with NaOH, monosaccharide content was determined by 3,5-dinitrosalicylic acid (DNS) colorimetric method, and hemicellulose content was calculated by multiplying monosaccharide content by 0.9. Lignin and cellulose were subsequently separated by 72.00% H₂SO₄ hydrolysis method. Monosaccharide content of hydrolysate was measured by anthrone colorimetric method and then multiplied by 0.9 to convert cellulose content. Lignin content was determined by drying and weighing the remaining filter residue at 105.0°C.

2.4 Root Paraffin Section Test and Microstructure Analysis

Two kinds of root materials were selected for the test, and 20 roots with a length of 10 mm were cut. After labeling, we made the paraffin sections by fixing, washing, staining, dehydration, transparency, wax embedding, and labeling (Li, 1987). Fixation test involved placing 10 mm of small root material in formaldehyde acetic acid ethanol (FAA) fixative solution for fixation to soften roots and maintain close to a normal state; saffron-fast green staining was used in staining test. Saffron was stained with 1.00% aqueous solution, and 0.50% wine semen (prepared with 95.00% alcohol) was used to fix green. Dehydration mixture was softened with hydrofluoric acid and dehydrated with an alcohol series. A Panoramic SCAN II (3DHISTECH Ltd., Budapest, Hungary) was used to scan and image all the tissue information in section, and scanning and browsing Case Viewer v.2.4 software was used to select target area of tissue for 10-fold expansion of samples (with tissue filling whole field of vision as much as possible). After scanning of imaging, we used Image-Pro Plus v.6.0 software to determine microscopic structural characteristics of roots of the two herbs, including area and area ratios of epidermis, cortex, and stele.

2.5 Data Analysis

Classification variables affecting root biomechanical properties were plant species, root water content, gauge length, and loading rate, and the continuous variable was root diameter. Effects of plant species, root water content, gauge length, and loading rate on root biomechanical properties were tested by ANOVA, and effects of continuous variable root diameter on root biomechanical properties were fitted by a power function or linear function. SPSS v.26.0 software was used for difference significance analysis, and Origin v.9.0 software was used for fitting and plotting.

3.1 Root Biomechanical Properties

Average root diameter of *S. aliena* was $0.289 (\pm 0.077) \text{ mm}$ ($n = 258$), average root tensile force was $4.942 (\pm 2.202) \text{ N}$ ($n = 258$), average root diameter of *P. crymophila* was $0.280 (\pm 0.070) \text{ mm}$ ($n = 269$), average root tensile force was $4.052 (\pm 1.678) \text{ N}$ ($n = 269$), and average root tensile force of *S. aliena* was greater than that of *P. crymophila* in all the treatments (Table 2). In addition, for the two herbs, with values ranging from 0.596 to 0.853 (Fig. 3 [Figure 3: see original paper]). Further analysis of variance of all the data of root diameter and root tensile force of the two herbs revealed that root diameters of the two herbs were not significantly different ($P > 0.050$), whereas root tensile force of *S. aliena* was significantly greater than that of *P. crymophila* ($P < 0.001$).

Average root tensile strength of *S. aliena* was $78.498 (\pm 28.435) \text{ MPa}$ ($n = 258$), average root tensile strength of *P. crymophila* was $67.541 (\pm 21.003) \text{ MPa}$ ($n = 269$), and average root tensile strength of *S. aliena* was greater than that of *P. crymophila* in all the treatments (Table 2). Furthermore, for the two herbs, with increasing root diameter, root tensile strength values ranging from 0.427 to 0.657 (Fig. 4 [Figure 4: see original paper]). A variance analysis of all the data of root tensile strength of the two herbs revealed that root tensile strength of *S. aliena* was significantly greater than that of *P. crymophila* ($P < 0.001$).

Average root fracture strain of *S. aliena* was $11.50\% (\pm 5.49 \pm 3.69\%)$ values ranging from 0.101 to 0.237, but correlation coefficient was small (Fig. 5 [Figure 5: see original paper]). A variance analysis of all the data for root fracture strains of the two herbs revealed that root fracture strain of *S. aliena* was significantly greater than that of *P. crymophila* ($P < 0.001$).

Average Young's modulus of *S. aliena* roots was $837.901 (\pm 498.999) \text{ MPa}$ ($n = 258$), average Young's modulus of *P. crymophila* roots was $901.184 (\pm 520.364) \text{ MPa}$ ($n = 269$), and average Young's modulus of *P. crymophila* roots was greater than that of *S. aliena* roots in all the treatments (Table 2). Moreover, for the two herbs, with increasing root diameter, Young's modulus values ranging from 0.562 to 0.775 (Fig. 6 [Figure 6: see original paper]). A variance analysis of all the data for root Young's modulus of the two herbs revealed that there was no significant difference in Young's modulus between roots of the two herbs ($P > 0.050$).

3.2 Root Stress-Strain Relationship

Roots of the two herbs were categorized into three diameter ranges, i.e., 0.10–0.20, 0.20–0.35, and 0.35–0.45 mm. One root from each range was selected to plot its stress-strain curves, as shown in Figure 7 [Figure 7: see original paper]. Results indicated that tensile stress strain curves of roots from both herbs under different treatments exhibited unimodal shapes without apparent necking phenomena. Hydrated roots of both herbs displayed elastic plastic brittle behavior. During initial tensile stage, roots underwent elastic deformation, where stress-strain relationship was approximately linear. The slope of this linear phase represents Young's modulus of the root. After reaching yield stress, roots exhibited a plastic strain-hardening response, with tensile stress increasing at a

slower rate than it did in pre-yield stage. Upon reaching the peak stress, roots showed brittle failure. In contrast, oven-dried roots of both herbs exhibited elastic-brittle behavior, resulting in a lack of significant plastic yield.

Regression analysis of stress and strain under four treatments revealed a power function relationship ($y=ax^b$) for both herbs. For hydrated roots, power function coefficient b was significantly less than 1.000, indicating that stress-strain relationship of roots of the two herbs did not conform to the Hooke's law and was an elastic plastic material. Conversely, for oven-dried roots, b approached 1.000, suggesting that stress strain relationship of roots of the two herbs essentially conformed to the Hooke's law and was an elastic material. Furthermore, stress strain characteristic curves of both herbs varied with root diameter under the four treatments. Under the same treatment, with the same strain, as the diameter increased, stress value decreased and Young's moduli of both species gradually decreased.

3.3 Root Chemical Composition and Microstructure

Table 3 shows test results of main chemical composition of roots of the two herbs. There was no significant difference in cellulose content between roots of the two herbs ($P>0.050$). The lignin content and lignin:cellulose ratio in *S. aliena* roots were significantly greater than those in *P. crymophila* roots ($P<0.050$), whereas the hemicellulose content in *P. crymophila* roots was significantly greater than that in *S. aliena* roots ($P<0.050$). Previous analyses revealed that the single-root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those of *P. crymophila* ($P<0.050$), whereas no significant difference in root diameter was detected between the two herbs ($P>0.050$). Based on existing data, we inferred that when difference in root cellulose content was very small, the higher the lignin content, the greater the lignin:cellulose ratio, the lower the hemicellulose content, and the better the root biomechanical properties.

Table 3 Test results of main chemical composition of roots of the two herbs

Species	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Holocellulose (%)	Lignin:cellulose ratio
<i>S. aliena</i>	26.26 $\pm$ 0.45 ^a	34.28 $\pm$ 0.57 ^a	20.75 $\pm$ 0.47 ^b	47.01 $\pm$ 0.75 ^a	1.305 $\pm$ 0.000 ^a *
<i>P. crymophila</i>	26.94 $\pm$ 0.44 ^a	24.12 $\pm$ 0.77 ^b	27.94 $\pm$ 1.53 ^a	54.87 $\pm$ 1.60 ^a	0.895 $\pm$ 0.012

Note: Different lowercase letters within the same column indicate significant differences between root chemical composition indices of the two herbs at $P<0.050$ level. Mean $\pm$ SE.

Root cross-sections of *S. aliena* and *P. crymophila* were composed of epidermis, cortex, endodermis, and stele (Fig. 8 [Figure 8: see original paper]). Proportion

of microstructure tissue was the greatest in cortex area, followed by stele area, and epidermis area was the smallest.

Fig. 8 Schematic diagram of root cross-sections of the two herbs. (a), *S. aliena*; (b), *P. crymophila*.

Further analysis revealed that with increasing root diameter of the two herbs, stele area, cortex area, and cortex area:total root area ratio increased gradually, whereas stele area:total root area ratio decreased gradually, and stele area, cortex area, and cortex area:total root area ratio were positively correlated with root diameter, whereas stele area:total root area ratio was negatively correlated with root diameter (Fig. 9 [Figure 9: see original paper]).

Fig. 9 Relationships of stele area and cortex area with root diameter of *S. aliena* (a) and *P. crymophila* (b) and of stele area:total root area ratio and cortex area:total root area ratio with root diameter of *S. aliena* (c) and *P. crymophila* (d)

3.4 Effects of Gauge Length, Root Water Content, and Loading Rate on Root Biomechanical Properties

Table 4 shows the results of variance analysis for root biomechanical properties of the two herbs. For hydrated roots with a given loading rate, gauge length had no significant effect on root tensile force or tensile strength of the two herbs ($P > 0.050$), but had a significant effect on fracture strain and Young's modulus of the roots ($P < 0.050$). Under 100 mm gauge length, fracture strain of roots of the two herbs was significantly lower than that under 50 mm gauge length ($P < 0.001$), whereas Young's modulus was significantly greater under 100 mm gauge length than under 50 mm gauge length ($P < 0.050$).

For the roots with a given gauge length and loading rate, root water content had no significant effect on the tensile force of the two herbs ($P > 0.050$), but had significant effects on the tensile strength, fracture strain, and Young's modulus of the roots ($P < 0.050$). Among them, tensile strength and fracture strain of hydrated roots of the two herbs were significantly greater than those of dried roots ($P < 0.050$), whereas Young's modulus was significantly lower than that of dried roots ($P < 0.001$).

For hydrated roots of a given gauge length, loading rate had no significant effect on root biomechanical properties of *P. crymophila* ($P > 0.050$), but had significant effects on tensile force, tensile strength, and fracture strain of *S. aliena* roots ($P < 0.050$). When loading rate was 20 mm/min, tensile force, tensile strength, and fracture strain of *S. aliena* roots were significantly greater than those at the loading rate of 200 mm/min ($P < 0.050$).

Table 4 Analysis of variation (ANOVA) result for root biomechanical properties of the two herbs

Influencing factor	Group	D	F	Tr	r	Er
Gauge length	SHL50R20	0.950	0.280	0.060	<0.001*	0.002*
	vs. SHL100R20					
	PHL50R20	0.780	0.470	0.060	<0.001*	0.020*
	vs. PHL100R20					
Root water content	SHL50R20	0.090	0.660	0.002*	<0.001*	<0.001*
	vs					
	SDL50R20					
	PHL50R20	0.420	0.230	0.015*	<0.001*	<0.001*
	vs. PDL50R20					
Loading rate	SHL50R20	0.750	0.033*	0.005*	<0.001*	0.240
	vs. SHL50R200					
	PHL50R20	0.570	0.620	0.220	0.180	0.720
	vs. PHL50R200					

Note: D, root diameter; F, tensile force of a single root at the breaking point; Tr, tensile strength of a single root; r, fracture strain of a single root; Er, Young' s modulus of a single root. * means significant difference.

4.1 Relationships Between Root Biomechanical Properties and Root Diameter

There have been few studies on the tensile mechanical properties of the roots of *S. aliena* and *P. crymophila*. Only Fu et al. (2023) and Zhao et al. (2024) studied the tensile mechanical properties of the roots of these two herbs. We found that tensile force was smaller and tensile strength and Young' s modulus were greater than those published data from Fu et al. (2023) and Zhao et al. (2024). The discrepancy of the result is mainly due to the relatively small average root diameter of the two herbs in this study. Our study also revealed that root diameter had a significant effect on the biomechanical properties of single roots of the two herbs. There was a positive power function correlation between tensile force of a single root and root diameter and a negative power function correlation between tensile strength and Young' s modulus of a single root and root diameter (Figs. 1-4). These findings were consistent with previous studies on root biomechanical properties (Zhang et al., 2019; Wu et al., 2021; Likitleruang et al., 2022; Phan et al., 2023; Fu et al., 2024). The negative relationship between root tensile strength and root diameter is due to the size effect exhibited by linear elastic fracture mechanics (Bažant and Kazemi, 1990). However, based on the size effect theory of fracture mechanics, exponential absolute value in relationship between tensile strength and diameter of herbaceous plant roots should not exceed 0.500. It can be seen from Figure 4 that the exponential absolute value is almost always greater than 0.500, which indicates that it is not enough to explain the relationship between tensile strength and root diameter only by the size effect theory of fracture mechanics. The exponential absolute

value greater than the theoretical value may be due to the difference in the chemical composition of roots with different diameters, which is verified by the results of Genet et al. (2005) and Zhao and Zhang (2007). They attributed this inverse relationship to higher cellulose content in fine roots, and found that root tensile strength increased with decreasing root diameter and increasing cellulose content for *Pinus pinaster* Ait., *Castanea sativa* mill., *M. sativa*, and *Digitaria sanguinalis* (L.) Scop. In addition, Phan et al. (2021) attributed this negative relationship between tensile strength and Young' s modulus of hydrated roots and root diameter to the effect of root water content. They found that there was a negative correlation between root water content and root diameter, whereas there were positive correlations of root water content with tensile strength and Young' s modulus for *C. zizanioides* and *Chrysopogon nemoralis* (Balansa) Holtum. These observations explain why tensile strength of roots increases with decreasing root diameter from a new perspective.

Under field condition, plant roots can directly improve soil shear strength through mechanical reinforcement and can also indirectly improve soil shear strength by reducing water content. Shear stress in soil matrix can be converted into root tensile strength through interfacial friction between root cortex and soil particles (Forster et al., 2022). In addition, tensile strength and Young' s modulus of roots control the magnitude of root tensile stress mobilized during shearing process, as does its resistance to tensile fracture in the limit state (Greenwood et al., 2004; De Baets et al., 2008), that is, tensile strength and Young' s modulus of roots resist shear and provide mechanical reinforcement for slope soil (Liang et al., 2017). Tensile strength of roots is considered as a fundamental parameter in most existing root reinforcement models (Wu et al., 1979; Pollen and Simon, 2005). When soil is subjected to shearing, roots that permeate deformed soil matrix are under tensile stress, thus providing reinforcement to the soil. This root reinforcement is normally considered as an additional shear strength, or so-called root cohesion (Wu et al., 1979; Waldron and Dakessian, 1981). Although the model from Wu (1976) and Waldron (1977) assumes that simultaneous roots fracture will overestimate root cohesion (Pollen and Simon, 2005; Schwarz et al., 2010), the model was still used to estimate the increase in soil shear strength because it allows for simple and quick calculation of soil reinforcement by roots using tensile strength and root distribution information. Our study showed that the roots of *S. aliena* and *P. crymophila* have relatively high tensile strength (78.498 and 67.541 MPa, respectively), and the two herbs have dense fibrous roots. According to the model, the roots of the two herbs can effectively improve the shear strength of surface soil, thereby significantly enhancing the resistance to erosion of surface soil and improving the stability of shallow slope.

4.2 Effects of Root Chemical Composition and Microstructure on Root Biomechanical Properties

Root chemical composition and microstructure (such as cellulose content, lignin content, and stele area:total root area ratio) also affect the root biomechanical properties (Genet et al., 2005; Zhang et al., 2014; Zhu et al., 2020; Yang et al., 2025). Therefore, changes in root chemical composition and microstructure during plant growth and decay play key roles in soil stability (Kamchoom and Leung, 2018; Yang et al., 2025).

Within a similar root diameter range, cellulose contents of *S. aliena*, *P. crymophila*, *D. sanguinalis*, *Zoysia matrella* (L.) Merr., and *Setaria viridis* (L.) P. Beauv. were relatively similar (Zhao and Zhang, 2007; Ye et al., 2017). Lignin content and lignin:cellulose ratio of *S. aliena* and *P. crymophila* were much greater than those of the other three herbs, and root tensile strengths of *S. aliena* and *P. crymophila* were also much greater than those of the other three herbs. Our study revealed that a high lignin content and high lignin:cellulose ratio corresponded to greater root tensile strength when difference in root cellulose content was small. If root structure is ignored, compared with the other three herbs, *S. aliena* and *P. crymophila* have a greater ability to reinforce the soil, which is also confirmed by the root tensile strength of these herbs. In addition, root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those of *P. crymophila* ($P < 0.050$); that is, roots of *S. aliena* presented relatively high biomechanical properties. This result was mainly due to the lignin content (34.28%) and lignin:cellulose ratio (1.305) of *S. aliena* roots were much greater than those of *P. crymophila* roots (24.12% and 0.895, respectively), although the hemicellulose content (27.94%) of *P. crymophila* roots was much greater than that of *S. aliena* roots (20.75%). In fact, lignin is an important complex organic polymer. As the skeleton of cell wall, lignin is rigid and nonperishable, providing strength, hardness, and structural integrity for cell wall (Tiimonen, 2007; Zhang et al., 2014), whereas hemicellulose has a random structure and low strength, which is only regarded as an amorphous filler (Saha et al., 2010). Therefore, the effect of hemicellulose on the tensile mechanical properties of roots is less than that of lignin.

Stele area, cortex area, and cortex area:total root area ratio of the two herbs were positively correlated with root diameter, whereas stele area:total root area ratio was negatively correlated with root diameter (Fig. 9). Stele area:total root area ratio can be understood as a concept of density, primarily attributed to the chemical constituents present within vessels and fibers of stele (Yang et al., 2025). A higher stele area:total root area ratio corresponds to greater density, a higher content of these components, and enhanced mechanical performance (Yang et al., 2025). Yang et al. (2025) also found that tensile strength of roots was positively correlated with stele area:total root area ratio for *Robinia pseudoacacia* L., *P. tabuliformis*, *Vitex negundo* L., and *Syzygium aromaticum* (L.) Merr. & L.M. Perry. Therefore, a change in plant root diameter affects stele area:total root area ratio and subsequently affects the biomechanical properties of plant roots.

4.3 Effects of Gauge Length, Root Water Content, and Loading Rate on Root Biomechanical Properties

The larger the root gauge length, the smaller the root tensile force, tensile strength, and fracture strain of the two herbs, and the larger the Young's modulus (Table 2). Previous studies have reached similar conclusions (Zhang et al., 2012; Yang et al., 2016b; Melese et al., 2021; Fu et al., 2024). This result can be attributed to the fact that roots grow in soils with complex physical and chemical properties, and defects inevitably occur. These defects are more likely to exist in longer roots (Moreton, 1969), that is, roots with longer gauge lengths have more flaws and micro-fissure than do those with shorter gauge lengths (Fu et al., 2024). Therefore, the longer the root gauge length, the lower the root tensile strength. However, compared with the research of Zhang et al. (2021), the Young's modulus of roots showed inconsistent variation trends. The possible reason is that the different species studied have different root anatomical structures and internal tissue compositions.

From hydrated roots to dried roots, tensile force, tensile strength, and fracture strain of roots of the two herbs decreased, Young's modulus increased (Table 2), and tensile strength and fracture strain of hydrated roots were significantly greater than those of dried roots ($P < 0.050$), whereas Young's modulus was significantly lower than that of dried roots ($P < 0.001$; Table 4). These observations might correlate with roots during drying process with two stages of response in tensile strength: at the first stage, with rapid increase of water loss, tensile strength of roots increased; at the second stage, with slow decrease of water loss, tensile strength of roots gradually decreased, and turning point between two stages can be considered as the tolerance limit of roots to water changes (Zhang et al., 2018). However, in contrast to our results, some studies reported that there was a negative correlation between root tensile strength and root water content (Boldrin et al., 2018; Zhang et al., 2019; Ekeoma et al., 2021; Melese et al., 2021; Wu et al., 2021). The relationship can be attributed to the root moisture content that increases root diameter and decreases tensile force simultaneously (Zhang et al., 2019). The increase in tensile strength after drying was due to root radial and axial contraction induced by root water potential drop (Boldrin et al., 2018). Besides, cell walls determine the mechanical strength of plant roots. Declined tensile force with increasing root moisture content is usually related to the accumulation of water in cell wall, which decreases the strength of bonds between organic polymers of cell wall (Hales and Miniati, 2017). Notably, all the dried roots used in the tensile test of Boldrin et al. (2018), Zhang et al. (2019), Ekeoma et al. (2021), and Melese et al. (2021) were obtained by air drying method; only Wu et al. (2021) refers to the dried roots obtained from drying at 50.0°C for more than 24 h to a constant weight. Compared with the two herbs used in this study, *C. zizanioides* has a larger root diameter and limited water loss during drying, that is, the water loss of plant roots may not have reached the tolerance limit, so tensile strength of dried roots is more than that of hydrated roots.

Loading rate had no significant effects on root tensile force, tensile strength, fracture strain or Young's modulus of *P. crymophila* ($P>0.050$; Table 4). Wu et al. (2021) studied root biomechanical variability of *C. zizanioides* and reported that loading rates (16 and 200 mm/min) also had no significant effect on root biomechanical properties when root diameter ranged from 0.10 to 1.58 mm. When loading rate was 20 mm/min, root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those at a loading rate of 200 mm/min ($P<0.050$; Table 4), which was consistent with the results of Li et al. (2015). Therefore, effect of loading rate on biomechanical properties of different plant species was various because fluctuation of root tensile strength between loading rates might be due to the inhomogeneity of root structure, root diameter, and possible flaws in roots (Zhang et al., 2012). In order to more precisely understand the effect of loading rate on root biomechanical properties, studies on different plant species are needed in the future.

4.4 Ecological and Practical Significance and Contributions to Sustainable Development

Plants *S. aliena* and *P. crymophila* used in this study are important native species in the upper reaches of the Yellow River. They have strong stress resistance and wide ecological adaptability and have important application in animal husbandry and ecological improvement in this area. The fibrous roots of these two herbs are developed and can form a dense root network to adapt to alpine, arid, and severely eroded environment. These characteristics play an important role in the ecosystem of the upper reaches of the Yellow River, which can stabilize slope soil, prevent soil erosion on the slope, and provide habitat for other plants and animals. On this basis, the biological slope protection measures of dominant herbs and traditional engineering measures, such as concrete grid slope protection and vegetation slope protection should be combined to stabilize the slope and reduce the impact and damage of landslide disasters (Leknoi et al., 2025). Moreover, the use of dominant native plants such as *S. aliena* and *P. crymophila* to carry out plant ecological restoration in the upper reaches of the Yellow River can directly promote the restoration of degraded land, increase vegetation coverage, and improve soil stability. In addition, *S. alina* and *P. crymophila* have dense fiber roots with high tensile strength and Young's moduli, which can effectively combine with surface soil to improve the shear strength of slope surface soil, thereby effectively enhancing the erosion resistance of slope soil, improving the stability of shallow slopes, and ultimately reducing the risk of landslide disasters caused by extreme rainfall and other climate events (Hong-In et al., 2024).

5 Conclusions

Mechanical reinforcement provided by plant roots can maintain surface soil and improve stability of shallow slopes. To investigate the effects of root diameter, gauge length, root water content, and loading rate on root biomechanical

cal properties, we carried out a series of uniaxial tensile tests on the roots of *S. aliena* and *P. crymophila*. Results revealed that root tensile force, tensile strength, fracture strain, and Young's modulus were significantly correlated with root diameter. Hydrated roots exhibited elastic plastic brittle behavior, whereas dried roots mainly exhibited elastic brittle behavior. Root tensile force, tensile strength, and fracture strain of *S. aliena* were significantly greater than those of *P. crymophila*, mainly because lignin content and lignin:cellulose ratio of *S. aliena* were significantly greater than those of *P. crymophila*. For these two plant species, gauge length and root water content had significant effects on root biomechanical properties, and loading rate had a significant effect on the root biomechanical properties of *S. aliena*. In conclusion, the two herbs can stabilize soil and prevent soil erosion and can be used as pioneer species for ecological restoration in the upper reaches of the Yellow River.

In the future, in situ shear tests on the two herbs with different vegetation coverages and bare land will be conducted to further highlight the influence and contribution of the two herbs to shear strength of slope topsoil.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

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References

- Apriyono A, Yuliana, Kamchoom V. 2023. Serviceability of cut slope and embankment under seasonal climate variations. *Acta Geophysica*, 71(2): 983-995.
- Bazant Z P, Kazemi M T. 1990. Size effect in fracture of ceramics and its use to determine fracture energy and effective process zone length. *Journal of the American Ceramic Society*, 73(7): 1841-1853.

- Boldrin D, Leung A K, Bengough A G. 2018. Effects of root dehydration on biomechanical properties of woody roots of *Ulex europaeus*. *Plant and Soil*, 431(1-2): 347-369.
- Burylo M, Rey F, Bochet E, et al. 2012. Plant functional traits and species ability for sediment retention during concentrated flow erosion. *Plant and Soil*, 353(1-2): 135-144.
- Capilleri P P, Cuomo M, Motta E, et al. 2019. Experimental investigation of root tensile strength for slope stabilization. *Indian Geotechnical Journal*, 49(6): 687-697.
- Chen X W, Kang Y, So P S, et al. 2018. Arbuscular mycorrhizal fungi increase the proportion of cellulose and hemicellulose in the root stele of vetiver grass. *Plant and Soil*, 425(1-2): 309-319.
- Chi N L. 2012. Determination of insoluble carbohydrates in plant fibers. MSc Thesis. Shanghai: Fudan University. (in Chinese)
- De Baets S, Poesen J, Reubens B, et al. 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil*, 305(1-2): 207-226.
- Eab K H, Likitlersuang S, Takahashi A. 2015. Laboratory and modelling investigation of root-reinforced system for slope stabilisation. *Soils and Foundations*, 55(5): 1270-1281.
- Ekeoma E C, Boldrin D, Loades K W, et al. 2021. Drying of fibrous roots strengthens the negative power relation between biomechanical properties and diameter. *Plant and Soil*, 469(1-2): 321-334.
- Forster M, Ugarte C, Lamandé M, et al. 2022. Root traits of crop species contributing to soil shear strength. *Geoderma*, 409: 115642, doi: 10.1016/j.geoderma.2021.115642.
- Fu J T, Zhao J M, Liu C Y, et al. 2023. Impact of slope position on the distribution and biomechanical properties of roots of dominant herbs. *Acta Agrestia Sinica*, 31(7): 2020-2030. (in Chinese)
- Fu J T, Zhou Z, Guo H, et al. 2024. Biomechanical behavior of grass roots at different gauge lengths. *Journal of Mountain Science*, 21(9): 3201-3214.
- Genet M, Stokes A, Salin F, et al. 2005. The influence of cellulose content on tensile strength in tree roots. *Plant and Soil*, 278(1-2): 1-9.
- Gray D H, Sotir R. 1996. *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*. New York: Wiley.
- Greenwood J R, Norris J E, Wint J. 2004. Assessing the contribution of vegetation to slope stability. *Geotechnical Engineering*, 157(4): 199-207.
- Hales T C, Miniati C F. 2017. Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. *Earth Surface Processes and*

Landforms, 42(5): 803–813.

Hong-In P, Takahashi A, Likitlersuang S. 2024. Engineering and environmental assessment of soilbag-based slope stabilisation for sustainable landslide mitigation in mountainous area. *Journal of Environmental Management*, 359: 120970, doi: 10.1016/j.jenvman.2024.120970.

Jiang K Y, Chen L H, Gai X G, et al. 2013. Relationship between tensile properties and microstructures of three different broadleaf tree roots in North China. *Transactions of the Chinese Society of Agricultural Engineering*, 29(3): 115–123. (in Chinese)

Kamchoom V, Leung A K. 2018. Hydro-mechanical reinforcements of live poles to slope stability. *Soils and Foundations*, 58(6): 1423–1434.

Lan H X, Peng J B, Zhu Y B, et al. 2022. Geological and surfacial processes and major disaster effects in the Yellow River Basin. *Science China Earth Sciences*, 52(2): 199–221. (in Chinese)

Leknoi U, Yienthaisong A, Likitlersuang S. 2025. Promoting use of vetiver grass for landslide protection: A pathway to achieve sustainable development goals in Thailand. *Environmental Development*, 54: 101155, doi: 10.1016/j.envdev.2025.

Li N, Chen L H, Yang Y J. 2015. Factors influencing root tensile properties of *Pinus tabulaeformis* and *Larix principis-rupprechtii*. *Journal of Beijing Forestry University*, 37(12): 77–84. (in Chinese)

Li Z L. 1987. *Plant Production Technology* (2nd ed.). Beijing: Science Press. (in Chinese)

Liang T, Bengough A G, Knappett J A, et al. 2017. Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering*, 109: 207–227.

Likitlersuang S, Phan T N, Boldrin D, et al. 2022. Influence of growth media on the biomechanical properties of the fibrous roots of two contrasting vetiver grass species. *Ecological Engineering*, 178: 106574, doi: 10.1016/j.ecoleng.2022.106574.

Mao Z, Wang Y, McCormack M L, et al. 2018. Mechanical traits of fine roots as a function of topology and anatomy. *Annals of Botany*, 122(7): 1103–1116.

Mao Z J, Geng M M. 2023. Study on tensile mechanical properties of alfalfa roots and the influencing factors. *Arid Zone Research*, 40(2): 235–246. (in Chinese)

Melese D T, Senadheera S, Legas A T. 2021. Effect of diameter, root moisture content, gauge length and loading rate on tensile strength of plant roots and their contribution to slope. *Lowland Technology International*, 22(4): 164–173.

- Moreton R. 1969. The effect of gauge length on the tensile strength of R.A.E. carbon fibres. *Fibre Science and Technology*, 1(4): 273-284.
- Nguyen T S, Likitlersuang S, Jotisankasa A. 2020. Stability analysis of vegetated residual soil slope in Thailand under rainfall conditions. *Environmental Geotechnics*, 7(5): 338-349.
- Ongpaporn P, Jotisankasa A, Likitlersuang S. 2022. Geotechnical investigation and stability analysis of bio-engineered slope at Surat Thani Province in Southern Thailand. *Bulletin of Engineering Geology and the Environment*, 81(3): 84, doi: 10.1007/s10064-022-02591-5.
- Phan T N, Likitlersuang S, Kamchoom V, et al. 2021. Root biomechanical properties of *Chrysopogon zizanioides* and *Chrysopogon nemoralis* for soil reinforcement and slope stabilisation. *Land Degradation & Development*, 32(16): 4657-4670.
- Phan T N, Leung A K, Kamchoom V, et al. 2023. Reinforcement losses in soil stabilisation due to decomposing roots of *Chrysopogon zizanioides* and *Chrysopogon nemoralis*. *Land Degradation & Development*, 34(4): 1080-1096.
- Pollen N, Simon A. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*, 41(7): 226-244.
- Prasetyaningtiyas G A, Kamchoom V, Leung A K, et al. 2024. Hydromechanical behaviour of a slope reinforced by grass roots under rainfall conditions. *Ecological Engineering*, 209: 107427, doi: 10.1016/j.ecoleng.2024.107427.
- Saha P, Manna S, Chowdhury S R, et al. 2010. Enhancement of tensile strength of lignocellulosic jute fibers by alkali-steam treatment. *Bioresource Technology*, 101(9): 3182-3187.
- Schwarz M, Preti F, Giadrossich F, et al. 2010. Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). *Ecological Engineering*, 36(3): 285-291.
- Shi Z H, Wang L, Liu Q J, et al. 2018. Soil erosion: From comprehensive control to ecological regulation. *Bulletin of Chinese Academy of Sciences*, 33(2): 198-205. (in Chinese)
- Stokes A, Douglas G B, Fourcaud T, et al. 2014. Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. *Plant and Soil*, 377(1-2): 1-23.
- Tiimonen H. 2007. *Lignin characteristics and ecological interactions of PtCOMT-modified silver birch*. PhD Dissertation. Finland: University of Oulu.
- Waldron L J. 1977. The shear resistance of root-permeated homogeneous and stratified soil. *Soil Science Society of America Journal*, 41(5): 843-848.

- Waldron L J, Dakessian S. 1981. Soil reinforcement by roots: Calculation of increased soil shear resistance from root properties. *Soil Science*, 132(6): 427-435.
- Wang X, Hong M M, Huang Z, et al. 2019. Biomechanical properties of plant root systems and their ability to stabilize slopes in geohazard-prone regions. *Soil and Tillage Research*, 189: 148-157.
- Wu T H. 1976. Investigation of landslides on Prince of Wales Island. Columbus: Ohio State University.
- Wu T H, Mckinnell III W P, Swanston D N. 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian Geotechnical Journal*, 16(1): 19-33.
- Wu Z, Leung A K, Boldrin D, et al. 2021. Variability in root biomechanics of *Chrysopogon zizanioides* for soil eco-engineering solutions. *Science of the Total Environment*, 776: 145943, doi: 10.1016/j.scitotenv.2021.145943.
- Yang Y J, Chen L H, Li N, et al. 2016a. Effect of root moisture content and diameter on root tensile properties. *PLoS ONE*, 11(3): e0151791, doi: 10.1371/journal.pone.0151791.
- Yang Y J, Chen L H, Li N. 2016b. How gauge length and loading rate influence the root tensile strength of *Betula platyphylla*. *Journal of Soil and Water Conservation*, 71(6): 460-466. (in Chinese)
- Yang Y Z, Yang J H, Ji J N, et al. 2025. How do stele and pores affect the macrobiomechanical properties of plant roots in tension?. *Plant and Soil*, 514(1): 919-935.
- Ye C, Guo Z L, Cai C F, et al. 2017. Relationship between root tensile mechanical properties and main chemical components of five herbaceous species. *Pratacultural Science*, 34(3): 598-606. (in Chinese)
- Zhang C B, Chen L H, Jiang J, et al. 2012. Effects of gauge length and strain rate on the tensile strength of tree roots. *Trees*, 26(5): 1577-1584.
- Zhang C B, Chen L H, Jiang J. 2014. Why fine tree roots are stronger than thicker roots: The role of cellulose and lignin in relation to slope stability. *Geomorphology*, 206: 196-202.
- Zhang C B, Zhou X, Jiang J, et al. 2019. Root moisture content influence on root tensile tests of herbaceous plants. *CATENA*, 172: 140-147.
- Zhang C B, Ma X, Liu Y, et al. 2021. Influence of various gauge lengths, root spacing and root numbers on root tensile properties of herbaceous plants. *Sains Malaysiana*, 50(9): 2499-2510.
- Zhang C B, Li R, Jiang J, et al. 2023. Effects of loading rate on root pullout performance of two plants in the eastern Loess Plateau, China. *Journal of Arid Land*, 15(9): 1129-1142.

Zhang L, Xia Z Y, Zhou Z J, et al. 2018. Experimental study on tensile properties and reinforcement ability of plant roots. *Nature Environment and Pollution Technology*, 17(3): 729–738.

Zhang Y, Zhu H L, Zhang K, et al. 2022. Relationship between tensile properties and microstructure of single root of three riparian plants. *Arid Zone Research*, 39(2): 572–583. (in Chinese)

Zhao J M, Hu X S, Fu J T, et al. 2024. Vegetation distribution pattern and their root mechanical property characteristics of giant landslide in the upper reaches of the Yellow River. *Acta Prataculturae Sinica*, 33(1): 33–49. (in Chinese)

Zhao L B, Zhang B G. 2007. Experimental study on root bio-mechanics and relevant factors of *Medicago sativa* and *Digitaria sanguinalis*. *Transactions of the Chinese Society of Agricultural Engineering*, 23(9): 7–12. (in Chinese)

Zhu J Q, Wang Y Q, Wang Y J, et al. 2020. How does root biodegradation after plant felling change root reinforcement to soil?. *Plant and Soil*, 446(1–2): 211–227.

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